Solar Powered Vacuum Membrane Distillation for Greywater Treatment Preceded by Electro-Coagulation for Prevention of Wetting

Mohammad Ramezanianpour[1], Muttucumaru Sivakumar[2], Ying Zhang[3]

[1]Lecturer, Department of Engineering and Architectural Studies, Ara Institute of Canterbury, Christchurch, New Zealand
[2]Associate Professor, Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong. NSW 2522, Australia
[3]PhD student, Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong. NSW 2522, Australia
Corresponding author's E-mail: matt.pour@ara.ac.nz

Abstract

Water recycling in a sustainable manner is increasingly being practiced for protection of water resources. Greywater generated from households can be readily used for recycling due to enhanced quality of this source compared to sewage. Vacuum membrane distillation (VMD), was selected in this research which comprises of evaporation and condensation processes that mimic the water cycle in nature. Solar energy was embedded into the VMD process to minimise energy consumption from non-renewable energy sources. The hydrophobic membrane assists the vaporization of greywater at lower temperatures by means of vacuum pressure on the permeate side. However, the membrane distillation (MD) process is rarely used for wastewater treatment due to the membrane wetting phenomenon which features the penetration of the feed water through the membrane pores. This phenomenon results from active surfactants present in detergents that reduces the contact angle between feed water and the surface of the hydrophobic membrane. Active surfactants are measured as linear alkylbenzene sulphonate (LAS). The main aim of this paper is to investigate the feasibility of a pre-treatment unit, electro-coagulation (EC), for removal of LAS in greywater. EC was incorporated to overcome the complexity of pore wetting for greywater treatment. A range of current density and circulation rate of EC unit was performed, and the quality of permeate water was monitored. It has been demonstrated that, after only 12 minutes of EC, the level of turbidity, total suspended solids (TSS), chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), total phosphorous (TP), electrical conductivity and faecal coliforms were reduced by an average 94.4%, 89.9%, 83.8%, 71.0%, 73.1%, 96.1%, 30.2% and 1.32 log, respectively. Finally, the EC unit was combined with the VMD system. Water quality and energy consumption were evaluated to determine the optimised level of current density and circulation rate for EC.

Keywords**:** Greywater treatment, Vacuum membrane distillation, Electro-coagulation, Solar energy, Membrane wetting.

1. INTRODUCTION

Treated greywater is a potential source of supplementary fresh-water supply due to its large-quantity production and less contamination compared with sewage. Alternative techniques are developed for greywater treatment, however research studies reveal that physical processes alone are not sufficient to meet the water quality guidelines especially for the removal of organics, nutrients and surfactants (Li et al. 2009). High quality effluent from greywater source is achievable using various combinations of biological or chemical processes with membrane filtration. On the other hand, sustainability considerations have led to the study of green technologies to produce high-quality fresh water that can be used for multiple purposes. One of the green technologies is the distillation method that mimics the evaporation and condensation process occurring in nature within a water cycle.

Among different configurations of membrane distillation (MD), vacuum membrane distillation (VMD) is selected for its highest flux rate. In addition, one of the major attractive features of VMD is its coupling to low-grade sources of energy (Qtaishat and Banat 2013). Vapour forms at saturation temperature respective to the vacuum pressure across a hydrophobic membrane. A number of other studies have also shown that distilled water can be produced efficaciously from seawater or brackish waters by VMD (Ramezanianpour and Sivakumar 2014). Besides, both electrical and thermal energies can be supplied by means of solar energy.

The hydrophobic nature of the membrane prevents the liquid solution from entering the pores. The only concern, however, remains the wetting phenomenon which can occur only if the pressure difference across the membrane pores exceeds the liquid entry pressure (LEP) of the feed water. To prevent pore wetting, parameters such as membrane material, porosity, pore size, thermal conductivity, surface tension of the solution and contact angle must be carefully considered (Li et al. 2009).

A tubular ultra-filtration (UF) module equipped with Polyvinylidene difluoride (PVDF) membranes and a polypropylene (PP) capillary MD module were incorporated for oily wastewater treatment (Gryta et al. 2006). UF process reduced the oil concentration to less than 5 ppm, and further purification by MD results in a complete removal of oil as well as 99.5% reduction of the total organic carbon (TOC) concentration. The permeate flux rate decreased from 1,300 kg/m^2d to 875 kg/m^2d after 50 h operation. Total dissolved solids (TDS) concentration was removed by 2.4% and 99.96% through an UF and UF followed by direct contact membrane distillation (DCMD), respectively. A commercial flat sheet Polytetrafluoroethylene (PTFE) was used in a DCMD process to treat olive mill wastewater (El-Abbassi et al. 2013). The effect of two processes, coagulation/flocculation and micro-filtration (MF) were investigated on the performance of DCMD. Concentration of total solids (TS), oil and TOC were reduced more efficiently by MF, however, better removal of chemical oxygen demand (COD) concentration achieved by coagulation/flocculation. A 35% water flux reduction rate observed after 76 h of of operation in a DCMD experiment. Wastewater containing NaCl and protein as well as the effluents produced during the regeneration of ion exchangers was used as feed for the DCMD process (Gryta et al. 2006). The necessity of appropriate pre-treatment for removal of foulants from the feed was reported in order to prevent wetting for the DCMD. The application of MD for industrial wastewater was successful, however, treatment of residential wastewater by means of MD has not been studied.

Greywater contains organic matter that can reduce the pressure difference across the membrane. The major cause of membrane wetting is related to the contact angle as show in Equation 1:

$$\Delta P = (- 2\, \sigma \cos\Theta) / r \qquad (1)$$

The contact angle must remain over 90° to ensure that the feed solution does not penetrate the membrane pores. The result of the contact angle with PP membrane sample is plotted for a variety of LAS stock solutions as shown in Figure 1. Increase in linear alkylbenzene sulphonate (LAS) concentration results in higher value of the absorbance which leads to a lower contact angle. However, it reaches a plateau at a specific high concentration. It was observed that for the LAS concentration of 12.5 mg/L (absorbance value of 3), the contact angle reached 86.9º.

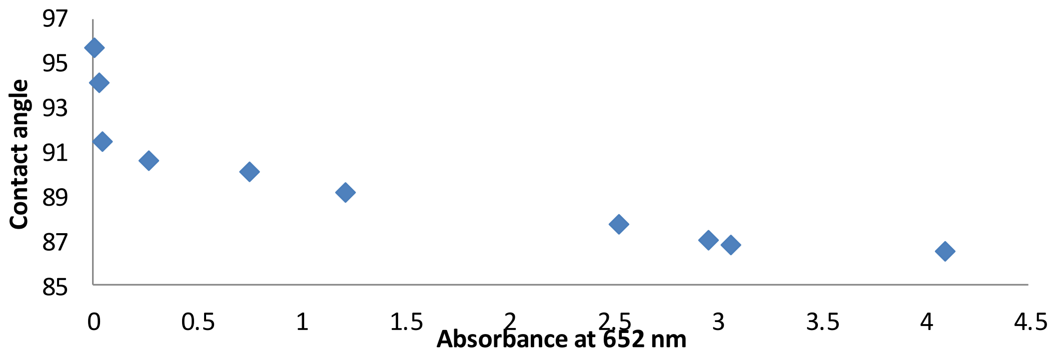

Figure 1 Contact angle for PP membrane versus the absorbance of LAS standard solutions

In this way, greywater treatment by means of MD techniques requires suitable pre-treatment units. It has been shown that the chemical processes are able to remove the suspended solids, organic materials and surfactants in low strength greywater. On the other hand, anaerobic processes are not sufficient for removal of organic substances and surfactants. The aerobic biological processes are suitable for medium and high strength greywater treatment (Li et al. 2009). Since the removal of surfactant is the main aim of this research, either a chemical process or an aerobic biological process is the most feasible solution for pre-treatment of greywater.

UF was suggested as an effective process for surfactant removal (Kowalska 2008). However, high concentration of surfactant results in the reduction of the permeate flux and critical micelles concentrations. The application of the ion-exchange process was also performed and indicated that the magnetic resin removes anionic surfactant successfully (Ge et al. 2004). UF followed by the ion-exchange unit was also suggested for surfactant removal. A bipolar electro-coagulation (EC)/electro-flotation process was carried out to treat laundry wastewater (Kowalska 2008). The bipolar design achieved acceptable removal of turbidity, COD, total phosphorous (TP) and surfactants in a wide pH range (5–9) at a short hydraulic retention time (HRT) (5–10 minutes.). Eight pieces of Ti plates and 21 pieces of Al plates were incorporated in the EC unit. The reactor volume and the effective area of each electrode were 2.8 L and 50 cm^2, respectively. This application removed 80% COD concentration, 95% LAS concentration and 99.9% turbidity. From a sustainability point of view, EC is more preferred than a chemical type of coagulation unit due to its flexible operation, avoiding the use of chemicals and EC lends itself to the application of solar power. EC as a pre-treatment unit is in accordance with the aim of this research to treat greywater by means of a sustainable and nature mimicry unit. The objectives of this paper are firstly to undertake experimental investigation of LAS removal from greywater and secondly to demonstrate the performance of the solar powered EC-VMD unit under real weather condition.

2. ELECTRO-COAGULATION SET-UP

Surfactant is rejected by means of the reaction between charged ionic species with ion of the opposite charge followed by flocculation. Iron or aluminium is usually selected as electrodes. Effects of operating parameters for the EC process such as electrode type (Al or Fe), initial pH (2–10), current density (5–80 A/m^2) and operating time (0–50 min) were investigated to determine the optimum operating conditions of the EC performance for treatment of paint manufacturing wastewater (Akyol, 2012). In terms of electrode type, Al electrodes were more successful than the Fe type with removal efficiencies of 94% and 89% for COD and TOC respectively. The operating parameters that affect EC include: electrolysis time, current density, rate of agitation, distance between electrodes, retention time, type of power supply, type and shape of electrode and pH. Current density is the most significant parameter of EC that influences the rate of coagulant dosage, rate of bubble production and size and growth of the flocculated species (Akyol, 2012). An increase in electrolysis time generates a larger number of metal hydroxides. However, further operation after the optimum electrolysis time has no effect on the pollutant removal efficiency.

The EC unit comprises of five parallel Al plates (200×200×3 mm) that has a total active area of 0.16 m^2. Various recirculation rates were carried out rather than the time of operation which results in more efficient coagulation by higher agitation rate. Thus, a circulating pump transfers greywater into the coagulation chamber as shown in Figure 2. ISO-Tech (IPS-1820D) DC variable power supply was used to adjust the current through the electrodes.

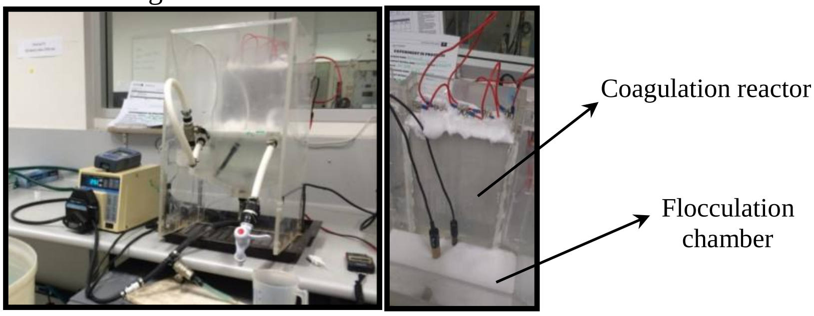

Figure 2. Electro-coagulator using Al electrodes for greywater treatment

Five different current densities (12.5, 25, 37.5, 50, 62.5 A/m^2) and three circulation rates (0.25, 0.50 and 0.75 L/min) were selected for the tests. For all 15 tests, pH and electrical conductivity were monitored online. Contact angle with a PP membrane was determined for each water sample collected in duplicates at 2, 4, 6, 8, 10, 30 and 60 minutes intervals of operation time.

3. SOLAR POWERED EC-VMD

An on-site solar powered EC-VMD system was designed and developed to investigate the performance of this system. The system is shown schematically in Figure 3. This system consists of two separate flow loops and a distillate channel. Electricity for the pumps and the EC unit is supplied by the two PV panels. Greywater is directed through the first loop from the feed tank through the glass coil condenser. The second loop recirculates water through the EC unit followed by the solar collector and the membrane. The EC unit not only treats greywater to achieve the required level of contact angle, but also heats the feed solution. The hollow fibre PP membrane module, MD02CP2N (MICRODYN, Germany) consists of 40 capillaries with 0.2 µm pore size, 70% porosity, 0.47 m length and 0.1 m^2 area. Vacuum pressure (7 kPa) is applied on the permeate side of the membrane by the N820 KNF laboratory vacuum pump (Javac, Australia). An online data acquisition system has been developed to monitor water quality and meteorological parameters during the treatment process.

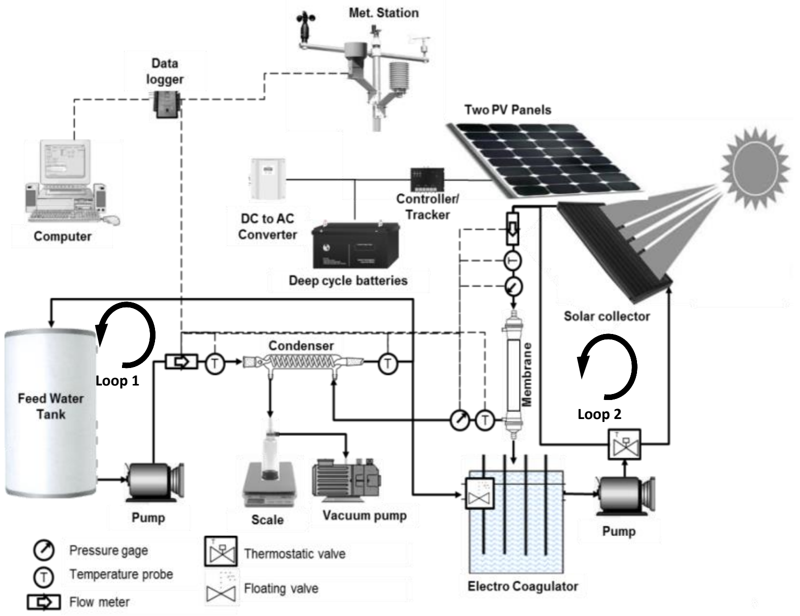

Figure 3 Solar powered electro-coagulation and vacuum membrane distillation system

4. EC UNIT TEST RESULTS FOR CONTACT ANGLE AND WATER QUALITY

Synthetic greywater prepared for the EC tests which were carried out for 60 minutes. Electrical conductivity of the sample was monitored online and was plotted in Figure 4. Higher current density reduced electrical conductivity of the greywater solution more rapidly. High current density increased the concentration of Al and more Al flocs resulting in a greater removal of TDS. However, as time progresses, the electrical conductivity of the effluent from the first chamber seems to level off. This is attributed to the fact that the chemical reactions have been reduced due to increase in pH. The other reason is that the subsequent production of Al ions remained in the solution without any chemical reactions. The electrical conductivity reduced to 310 and 330 µS/cm in all conditions except for the circulation rate of 0.25 L/min. The effect of EC on pH was also monitored and graphed for each test. Higher contact angle is achieved with higher current density and higher circulation rate. Figure 4 depicts that for all tests the contact angle increased sharply for the first 5 to 10 minutes of operation. The results show that a minimum operation time of 5 to 10 minutes is required to achieve a contact angle above 100°. The circulation rate of 0.25 L/min required 60 minutes of treatment to reach 100° contact angle in the case of the highest current density application as shown in Figure 4 a. The circulation rate of 0.5 L/min significantly increased the contact angle from an average 78° to 100° in 50, 19, 8, 5 and 6 minutes of treatment for 12.5 A/m^2, 25 A/m^2, 37.5 A/m^2, 50 A/m^2 and 62.5 A/m^2, respectively as shown in Figure 4 b. Similar improvement was observed for the circulation rate of 0.75 L/min where the contact angle increased from an average 78° to 100° in 44, 14, 8, 5 and 5 minutes for 12.5 A/m^2, 25 A/m^2, 37.5 A/m^2, 50 A/m^2 and 62.5 A/m^2, respectively as shown in Figure 4 c.

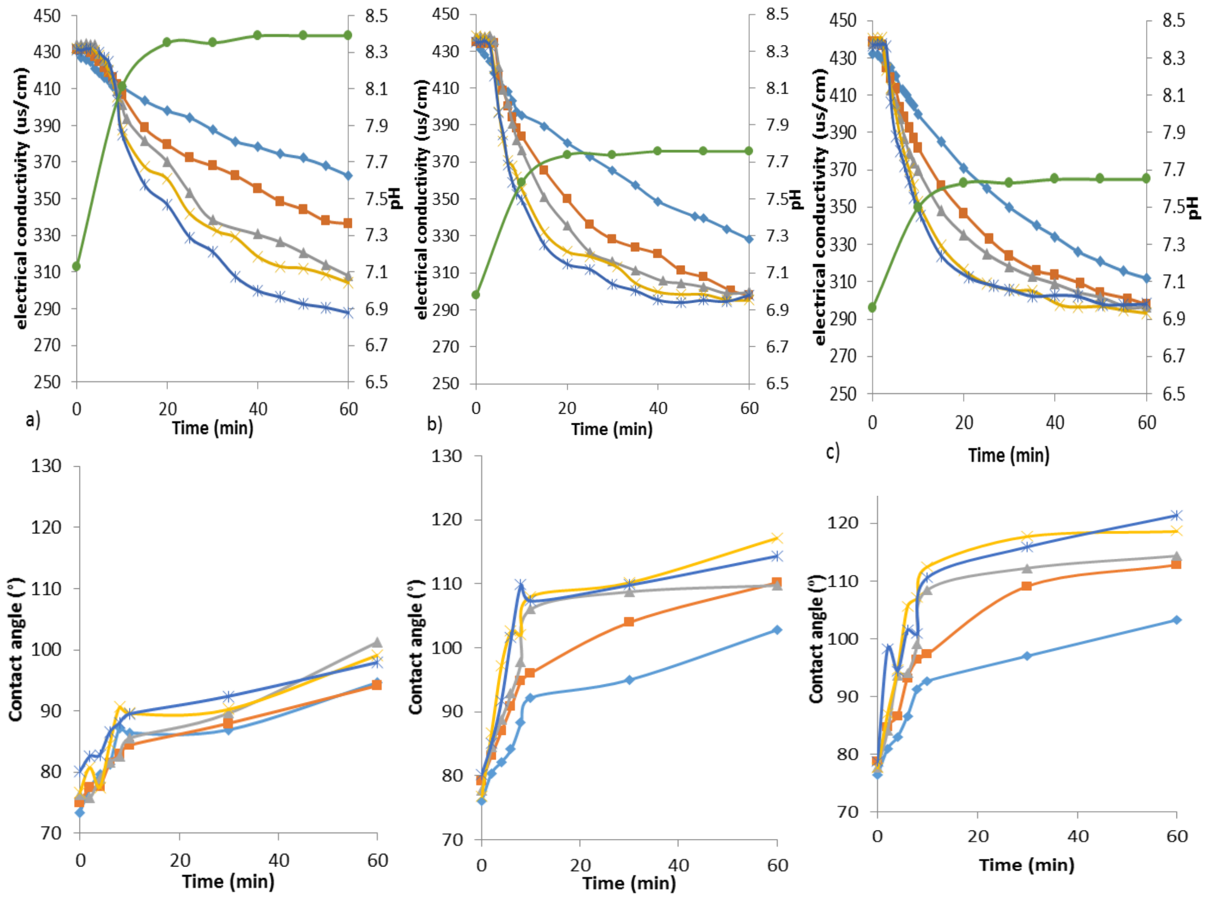

Figure 4 Electrical conductivity, pH (●) and contact angle measurements with operation time for a) 0.25 L/min, b) 0.5 L/min and c) 0.75 L/min circulation rate at various current densities (♦) 12.5 A/m^2, (■) 25 A/m^2, (▲) 37.5 A/m^2, (✕) 50A/m^2 and (*) 62.5 A/m^2

Water quality parameters were measured before and after treatment by the EC unit. The EC process removed 94.4 % of turbidity which had an initial turbidity value of 25.5 NTU. Flocculation followed by either sedimentation or flotation will reduce the concentration of suspended solids. TSS also reduced from 180 mg/L to an average of 3.90 mg/L at all current densities. TOC concentration was reduced by 71.0 % from 54.5 mg/L. Greywater COD concentration also decreased from 404.5 mg/L to 65.5 mg/L which illustrates the removal of organic matter from the solution. The COD and TOC concentrations were reduced by the increase of current density. This is mainly attributed due to the increase in size of precipitates, increased rate of bubble-generation and decreased bubble size when current density increases. TN and TP concentrations decreased by an average 73.1% and 96.1%, respectively. The main reaction is between phosphate and nitrate with aluminium. The Al:TP ratios were 1.32, 2.65, 3.97, 5.23 and 6.62 for the 12.5 A/m^2, 25 A/m^2, 37.5 A/m^2, 50A/m^2 and 62.5 A/m^2 current densities, respectively. The EC process also showed a low 1.32 log removal of faecal coliforms. It was found that as the current densities increased the contaminants quantity decreased. F. Coliforms counts significantly decreased to 328 cfu/100mL, 90 cfu/100mL, 60 cfu/100mL, 6 cfu/100mL and 4 cfu/100mL for current density 12.5 A/m^2, 25 A/m^2, 37.5 A/m^2, 50A/m^2 and 62.5 A/m^2, respectively, due to higher temperature released to the solution at higher current density.

5. SOLAR POWERED COMBINATION OF EC AND VMD

Experimental results of the permeate water from EC permit the solution to pass through the hydrophobic membrane. The EC unit was placed after the condenser to increase the temperature of the solution in the second loop. The EC unit was also operated at the optimum current density of 37.5 A/m^2. Greywater was treated through the system for five hours as shown in Figure 5. The maximum flux rates of 2.4 $L/m^2.h$ were achieved between 13:15 to 14:15 hours due to the highest solar radiation at 13:00. The feed solution temperature increased marginally from 38 to 49 °C between 11:00 to 13:00. This is attributed to the solar irradiance. Since, the vacuum pressure was constant, the temperature was the significant parameter in the variation of the permeate flux rate.

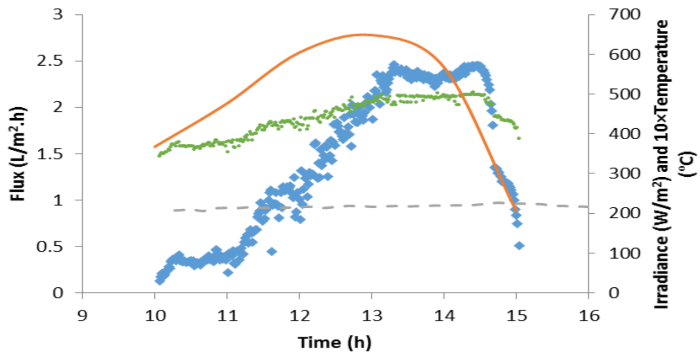

Figure 5 The permeate flux (♦) for solar powered EC-VMD, solar irradiance (—) and ambient temperature (--) and feed water temperature (●) during a day

6. CONCLUSION

The stand-alone solar powered EC-VMD system was successful in treating greywater. Extraction of vapour on the permeate side of the membrane illustrated the successful removal of LAS from greywater. This was achieved by only 5 minutes of electrocoagulation at a current density of 37.5 A/m^2 and a circulation rate of 0.5 L/min. It was concluded that the EC unit not only performed well as a pre-treatment process to treat the permeate water by the PP hydrophobic membrane but also it improved the water quality of the greywater. Over 90% removal of TSS concentration, TP concentration and turbidity value were achieved by means of EC. These advantages can result in a higher permeate flux rate and higher membrane life time. The permeate was heated by the solar thermal panel before it goes into the membrane. The operating permeate pressure and feed water flow rate was kept constant during the day. The permeate flux varied as a result of the changing feed-water temperature which depends on the incident solar energy as well as the efficiency of the solar thermal panel. Maximum distillate flux 2.4 L/m^2h occurred between 13:15 to 14:15 due to the increase of solar radiation before 13:00.

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